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Numerical Study of Soil Properties on Heat Transfer Between Soil and Cold Storage

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دراسة عددية لخواص التربة في الانتقال الحراري بين التربة ومخزن التبريد

يعرض هذا البحث نتائج دراسة الخواص الحرارية للتربة على الانتقال الحراري من تربة اسفل أرضية مخزن التبريد. كما انه يعرض تأثير كثافة التربة و الموصل الحراري والانتشار على الانتقال الحراري بين مخزن التبريد والتربة. وقد طبقت هذه الدراسة في مدينة جـــــده لحساب درجات الحرارة المختلفة وتقييم التدفق الحراري بفرضية أن درجات الحرارة المختلفة للتربة تكون بحالة "موجة جيبيه" . وقد أثبتت الدراسة تأثير كمية الطين وحجم محتوى الماء وكثافة التربة على التدفق الحراري . كما أن الدراسة الحالية تفيد في توجيه الدراسات والتجارب المستقبلية المتعلقة بتجمد التربة.

Abstract

This paper presents the numerical investigation of the soil properties on the heat transfer from the soil below cold store. The effect of thermal conductivity, diffusivity and density of the soil on heat transfer between cold store and soil were studies for two cases. The two cases for cold store are one floor building erected directly on the ground or lifted by about 1.2 m above ground level.

The analysis was applied in Jeddah, to calculate temperature variation and evaluate heat transfer in the assumption of soil surface temperature variation in the form of sine-wave. The results have shown the effect of clay content, volumetric water content and the soil density on heat flux. The present results are useful guides for the future experimental and computational studies on soil freezing and related research work.

Key words: Freezing, Clay, Insulation, Density, Volumetric water, Heat Flux

NOMENLCATURE

A	Amplitude of the surface temperature, ($^{\circ}C$).
C	Cold store length, (m).
D	The model depth, (m).

$D1$	The model depth, (m).
H	The insulation thickness, (m).
T	The temperature, ($^{\circ}C$).
T_s	Soil surface temperature, ($^{\circ}C$).
T_c	Cold store surface temperature, ($^{\circ}C$).
T_a	Soil average temperature, ($^{\circ}C$).
W	Wall thickness, (m).
$f(z,t)$	The solution of one-dimensional time dependent conduction heat transfer equation, ($^{\circ}C$).
t	Time, (day).
$t_{\max}$	The time of the occurrence of the maximum surface temperature, (day).
x, z	Surface coordinate and depth coordinate, (m).
ω	Frequency of temperature fluctuation, ($1/day$).
α	The thermal diffusivity, (m^2/s).
$\Delta x, \Delta z$	The increments in the direction x and z, (m).
Δ_{ins}	The increments in the insulation, (m).
Δ_s	The increments in the soil, (m).

INTRODUCTION

When soil, soil volumetric water, or wet soil is cold under $0\ ^{o}C$ temperature, the soil becomes frozen. If soil expands when frozen, the volume change is called frost heave (Jumikis 1966). Frost damage to building foundations, walls, driveway, walks and similar structures is common to any ground exposed to cold, but it is not equally serious in all areas, therefore; the yearly cost of this damage is high(Viklander 1998, Pan 2002).

In the most part of high altitudes and latitudes the ground freezes during winter to a depth varying from a few centimeter (inches) to several meters (feet) (Burn 1976). Soil is artificially frozen in certain areas such as soil around Liquid Natural Gas(LNG), refrigeration pipes, and soil under the cold storage.

Cold stores can be classified as one floor or multi-floor buildings. Cold stores are recommended to have a basement or a place for the freezing sections away from the ground floor. Prefabricated cold stores which are widely used in Jeddah, Saudi Arabia, due to increase of population and shortage of food production, lead to increase the rate of imported frozen products. Most of the cold storages are one floor building each erected directly on the ground or lifted by about 1.2 m above ground level.

When wet soil freezes, the main process is the physical change of soil water from liquid to solid that turns the soil into a hard mass and the volume becomes larger, which leads to damage building foundations, retaining wall, driveways, and similar structures. Soil freezing may occur in Jeddah especially with the rise of ground water level. Basamed (2001) shows that the ground water level is less than 2.5 *m* in the West and in the Mid-East of Jeddah.

Heat transfer studies below cold stores are very important. However there have been many studies of heat transfer from buildings to ground, or from the ground to buildings. Salah El Din (1988) studies numerical and experimental heat transfer in soil below cold stores for three different samples representing sand, sand clay and clay soils and the effect of volumetric water content up to 40% in Alexandria, Egypt . Zhou et al, (2002) studies numerical and experimental heat losses from twin room (test house) and investigate the effects of edge insulation on the heat transfer. Ground temperature, soil freezing, frost heaving of foundation have been studied in cold regions and below cold storage buildings (Penner 1962, Brown 1965, Penner et al. 1970 and Williams et al. 1976).

The review of literature in the current study shows that the analysis of heat transfer in soil below cold stores is still uncovered. Therefore the present work is directed towards the numerical investigation of the heat transfer between soil and cold store, to show the effect of soil properties (thermal conductivity, diffusivity, density of the soil, clay content, volumetric water content, cold store temperature, insulation thickness, wall thickness cold store length and the level of the cold store) on rate of heat transfer for two cases. The two cases for cold store are one floor building erected directly on the ground, and the other lifted by about 1.2 m above ground level.

MATHEMATICAL MODEL

Governing Equation

The two-dimensional heat conduction time-dependent equation is considered. It is assumed that the heat is transferred by conduction, while convection and radiation are neglected. In addition, the thermal properties of the material are considered constant. Figure (1) shows the schematic diagram of the heat transfer model in which half of the domain is below and adjacent to cold store was considered (taken into consideration). The equation for the soil and insulation can be written in Cartesian form as

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{1}$$

The initial and boundary conditions are:

$T(x,z,0) = f(z,0)$

$T(H,z,t) = f(z,t)$, $\quad T(0,z,t) = \dfrac{\partial T}{\partial x} = 0$, $\quad T(x,D,t) = T_a$,

$T(x,0,t) = T_c$ for $0 \le x \le C$, $\quad T(x,0,t) = T_s = f(0,t)$ for $(C+W) \le x \le H$

where

$$T_s = f(z,t) = T_a + A\, e^{zd}\, \sin(\omega\, t - dz + c) \quad (2)$$

which, is the solution of equation (1) for one-dimensional heat conduction time-dependent, where T_a is an average measured soil temperature over five years, and A is the amplitude of the surface temperature at time $t = 0$, and $d = \sqrt{\omega / 2\,\alpha}$,

$c = \dfrac{\pi}{2} - \omega\, t_{\max}$.

The temperature at the interface between two different materials; such as soil and insulation can be calculated by the energy balance, which, satisfies the following relation:

$$k_{ins}\left(\frac{\partial T}{\partial z}\right)_{ins} = k_s\left(\frac{\partial T}{\partial z}\right)_s \quad (3)$$

where *ins* and *s* denotes insulation and soil respectively.

At the interface an equivalent thermal conductivity k_{eq} can be calculated as follows:

$$k_{eq} = \left(\Delta_{ins}\, k_{ins} + \Delta_s\, k_s\right) / \left(\Delta_{ins} + \Delta_s\right) \quad (4)$$

The second–order algorithm implemented to integrate the two-dimensional heat conduction time-dependent equation is fully explicit (Barakat et al. 1966). The temperature $T_{i,j}$ at any time level my be given by:

$$T^{n+1}_{i,j} = (u^{n+1}_{i,j} + v^{n+1}_{i,j}) / 2 \quad (5)$$

and

$$u^{n+1}_{i,j} = a\, u^n_{i,j} + b\left(u^{n+1}_{i-1,j} + u^n_{i+1,j}\right) + c\left(u^{n+1}_{i,j-1} + u^n_{i,j+1}\right) \quad (6)$$

$$v^{n+1}_{i,j} = a\, v^n_{i,j} + b\left(v^n_{i-1,j} + v^{n+1}_{i+1,j}\right) + c\left(v^n_{i,j-1} + v^{n+1}_{i,j+1}\right) \quad (7)$$

where

$a = (1-\lambda)/(1+\lambda)$

$b = \left(\Delta t/(\Delta x)^2\right)/(1+\lambda)$

$c = \left(\Delta t/(\Delta y)^2\right)/(1+\lambda)$

$$\lambda = \Delta t\left[\frac{1}{(\Delta x)^2}+\frac{1}{(\Delta y)^2}\right] \le \frac{1}{2} \tag{8}$$

Equation (5) indicates that $T_{i,j}$ is the arithmetic average of $u_{i,j}^{n+1}$ and $v_{i,j}^{n+1}$. $u_{i,j}^{n+1}$ can be explicitly calculated by using equation (6), where the calculation starts from the grid point near to *x=0* and *z=0* in the sequence of increasing *i* and *j*. Similarly, $v_{i,j}^{n+1}$ can be explicitly calculated by using equation (7), where the calculation starts from the grid point near to *x=H* and *z=D* in the sequence of decreasing *i* and *j*. In equations (5) and (6) the $u_{i,j}^{n+1}$ and $v_{i,j}^{n+1}$ which are calculated for one step become $u_{i,j}^{n}$ and $v_{i,j}^{n}$ for the next step.

Heat flux calculation

The average heat flux on the floor can be calculated as follow:

$$q_{av} = \frac{1}{N}\sum_{i=1}^{N} q_i \tag{9}$$

where q_i is the heat flux through the floor, which is given by

$$q_i = k_{ins}\frac{T_i - T_c}{\Delta z} \qquad \text{for } 1 \le i \le N \tag{10}$$

where *N* is the number of node in the x-direction.

Accuracy Of Numerical Results

The numerical program is written based on the above algorithm, whereas the results are compared with the exact solution in the following conditions:

$T_c = T_s$, $\Delta x = \Delta z = 0.1\,m$, $t_{\max} = 215\,days$,

$T_s|_{t=0} = 13.6\ ^{\circ}C$, $T_a = 22.9\ ^{\circ}C$, $A = 10.9\ ^{\circ}C$,

$k_s = 0.377\ W/m\ ^{\circ}C$, $\alpha_s = 4.63\times10^{-7}\ m^2/day$.

Table 1. shows good accuracy of the numerical temperature T_{nu} and the exact temperature T_{ex}, for different depths and times. The maximum *Percentage Error*

which was calculated by using equation (8) does not exceed 3% (*Percentage Error* = 2.981) for $z = 0.1$ *m* and $t = 210$ *days*.

At time of 60 days (February) , shows that the exact temperature increased as the depth increased from $T_{ex} = 13.43\ ^oC$ at *z=0.1m* to $T_{ex} = 22.98\ ^oC$ at *z=9.7m*, and at time of 210 days (June: where high temperature is at the surface in summer), shows that the exact temperature decreased as the depth increased from $T_{ex} = 33.21\ ^oC$ at *z=0.1m* to $T_{ex} = 22.88\ ^oC$ at *z=9.7m*; and at time of 360 days (December), shows that the exact temperature increased as the depth increased from $T_{ex} = 14.85\ ^oC$ at *z=0.1m* to $T_{ex} = 22.89\ ^oC$ at *z=9.7m*. Note that over all three time levels (60, 210 and 360 days) the exact temperature at depth z=9.7m becomes very close to soil average temperature $T_a = 22.9\ ^oC$. Equation (2) shows that the amplitude of the temperature decreased exponentially with distance from the surface at a rate dictated by the time necessary for one complete cycle.

$$Percentage\ Error = \left(\frac{T_{ex} - T_{nu}}{T_{ex}} \right) \times 100 \tag{11}$$

	60 (*days*)			210 (*days*)			360 (*days*)		
Z(*m*)	T_{ex}	T_{nu}	*Error*	T	T_{nu}	*Error*	T	T_{nu}	*Error*
0.1	13.43	13.46	-0.223	33.21	32.22	2.981	14.89	14.85	0.269
0.2	13.68	13.73	-0.365	32.68	32.69	-0.031	15.55	15.49	0.386
1.2	16.67	16.78	-0.660	27.90	27.88	0.072	20.65	20.59	0.291
4.2	22.03	22.30	-1.223	22.21	22.03	0.810	24.23	24.14	0.394
9.7	22.98	22.90	0.348	22.88	22.83	0.219	22.85	22.89	0.175

Table 1: The numerical and exact solution of the temperature, ^oC for different depths and times.

NUMERICAL SIMULATION RESULTS

Finite Difference Representation:

A two dimensional finite-difference representation of the test model is shown in figure (1). After preliminary analyses of this problem, to insure the far-field boundary condition applied with minimum influence on the result, the overall dimensions of the domain are approximately $H = 18$ *m* length by $D = 10.2m$ depth (the depth where the ground temperature is essentially constant throughout the year) and cold store width $C=9$ *m*, with graded mesh has been adopted with $\Delta x = \Delta z = 0.1m$.

The initial temperature distribution throughout the domain is assumed to be a function of z-direction only and can be calculated by equation (2). Boundary condition applied to the model is shown in figure (1), since the plane at $x = 0$ is an adiabatic the boundary will be as $\frac{\partial T}{\partial x} = 0$, and the boundary at the far field ($x = H$) and $z = D$ can be represented by equation (2).

The temperature of the cold store floor surface is considered to be constant, while the temperature at the wall is assumed to be changed linearly between the soil surface temperature T_s and cold store surface temperature T_c and can be represented by the following equation.

$$\frac{T - T_c}{T_s - T_c} = \frac{x - C}{W} \qquad \text{where } C \leq x \leq (C + W) \qquad (12)$$

Material property

Heat transfer in the soil depends on the thermal properties of the soil. Since the thermal properties depend on many factors such as volumetric water content, clay content, density, particle size and shape , chemical composition, etc., the investigation of heat transfer between the soil and cold store carries out to study the effect of the thermal conductivity and diffusivity with volumetric water content up to 30 % and clay content up to *60 %* for density *1200, 1500* and *1800* kg/m^3. There are many studies and investigations on the thermal properties of the soil in the literature such as Miller et al. (1999), Fuhrer (2000), Abu-Hamdeh (2000), Nofziger et al. (2002) and Gori et al. (2003). Based on the above investigation the soil properties used in current study are considered to be constant for each run (case).

RESULTS and DISCUSSION

The first case studied for the ground heat losses when the cold store floor is laid directly on the soil surface (see Fig. 1.) and the dimension is *18 m* by *10.2 m* with *0.2 m* insulation thickness (polyurethane) below it, and investigates the main parameters that affect the average heat flux at certain time such as: cold store temperature, wall thickness, insulation thickness, width of cold store and soil thermal properties (thermal conductivity and thermal diffusivity) which is affected by variation of clay content, volumetric water content, soil density. Based on the result of the first case the second case investigated when the cold store floor is lifted up from the soil surface by *1.2 m* and studies the effect of cold store level on heat flux.

It is clear from Fig. 2 that the temperature is less than $-5\ ^{o}C$ at depth of less than *2.5 m*. for case when C = *9 m*, D1 = *0.4 m*, $T_c = -20^{o}C$, volumetric water

content = *0.3* m^3/m^3, clay content = *30%*, density $\rho = 1500\,kg/m^3$, $k_s = 1.82\,W/m^\circ C$ and $\alpha = 0.079\,m^2/day$. This result has been achieved after 215 days of operation for the first case.

Effect of clay content

Fig.3. shows the variation of average heat flux with clay content up to *60 %* in the first case for *C=9 m, D1=0.2 m,* $T_c = -20\ ^\circ C$, density $\rho = 1800\ kg/m^3$, and volumetric water content=0.3 m^3/m^3, at *t=215 days*. It is clear that as the clay content (%) is increased heat flux $q_{av}\left(W/m^2\right)$ is also increased. The result also shows that when the soil becomes soft (when clay content is greater than 30%) we have a rapid increase in heat flux.

Effect of volumetric water content

Fig.4. shows the variation of average heat flux $q_{av}\left(W/m^2\right)$ with volumetric water content up to 0.3 (m^3/m^3) in the first case for C=9 m, D1=0.2 m, $T_c = -20\ ^\circ C$ and clay content=30 % at *t=215 days*. It is clear that as the volumetric water content is increased to about 0.1 (m^3/m^3) heat flux is decreased but for volumetric water content between 0.1 *to* 0.3 (m^3/m^3) heat flux becomes near constant for all three densities. Also the result shows that as density increased the heat flux is decreased

Effect of density

Fig. 4 shows the effect of soil density (kg/m^3) on average heat flux $q_{av}\left(W/m\ \right)$ in the first case. While Fig. 5 shows the variation of average heat flux with density in the first case for C=9 m, D1=0.2 m, $T_c = -20\ ^\circ C$ clay content = 30% and volumetric water content = 0.3 m^3/m^3, at *t = 215 days.* It is clear that as the density is increased, heat flux is decreased.

Effect of cold store temperature

Fig.6. Shows the variation of average heat flux with cold store surface temperature in the first case for C =9 *m*, D1=*0.2m*, $\rho = 1800\ kg/m^3$, $T_c = -20\ ^\circ C$, volumetric water content = 0.3 m^3/m^3, clay content =30%, at *t = 215 days.* It is clear that as the cold store surface temperature is decreased heat flux is increased.

Based on the above results in the first case the following parameters are selected to study the effect of insulation thickness, wall thickness, cold store width and cold store level:

Density = 1500 kg/m^3 volumetric water content = 0.3 (m^3/m^3)
clay content = *30 %* cold store surface temperature $T_c = -20\ ^oC$

Effect of insulation thickness

Fig. 7. Shows the variation of average heat flux $q_{av}\ (W/m^2)$ with insulation thickness (*m*) in the first case for C=9 m, $\rho = 1500\ kg/m^3$, $T_c = -20\ ^oC$, volumetric water content = 0.3 m^3/m^3, clay content = 30%, at *t = 215 days.* It is clear that as the insulation thickness is increased, average heat flux is decreased.

Effect of wall thickness

Fig.8. shows the variation of average heat flux $q_{av}\ (W/m\ )$ with wall thickness (*m*) in the first case for C=9 m, D1=0.2 m, $\rho = 1500\ kg/m^3$, $T_c = -20\ ^oC$, volumetric water content = 0.3 m^3/m^3, clay content = 30%, at *t = 215 days.* It is clear that as the wall thickness is increased, heat flux is decreased

Effect of width of cold store

Fig. 9. shows the variation of average heat flux $q_{av}\ (W/m\ )$ with width of cold store (*m*) in the first case for D1= 0.2 *m*, $\rho = 1500\ kg/m^3$, $T_c = -20\ ^oC$, volumetric water content = 0.3 m^3/m^3, clay content =30%, *t = 215 days.* It is clear that as the width of cold store is increased heat flux is decreased.

The second case studied for the ground heat losses when the cold store floor is lifted up from the soil surface by *1.2 m,* for C = *9 m*, D1 = *0.4 m*, $T_c = -20^oC$, volumetric water content = *0.3* m^3/m^3, clay content = *30%*, $\rho = 1500\,kg/m^3$, $k_s = 1.82\ W/m^oC$ and $\alpha = 0.067392\,m^2/day$. The temperature is less than $-5\ ^oC$ at depth of less than 2.5 *m* as shown in Fig. 10. This is a very closed result to that of the first case as shown in Fig. 2. Since the ground water level is less than 2.5 m in the West and in the Mid-East of Jeddah, soil frozen is expected below cold store in both models.

Effect of cold store level

Fig.11. shows the variation of average heat flux with cold store level the cold store lifted up to *1.2 m* for C=9 *m*, D1=0.2 *m*, $\rho = 1500\ kg/m^3$, $T_c = -20\ ^oC$, volumetric water content = 0.3 m^3/m^3, clay content =30%, *t = 215 days.* It is clear that as the cold store level is increased heat flux is increased.

CONCLUSIONS

The present numerical investigation results in conclusions summarized as follows:

1. In both cases the soil temperature is negative (less than $-5\ ^oC$) at depth less than *2.5 m*, which leads to soil freezing.
2. Heat flux is decreased as soil density is increased.
3. Heat flux is decreased as volumetric water content is increased to about $0.1\ (m^3/m^3)$, then heat flux becomes near constant for all three densities for volumetric water content between $0.1\ \textit{to}\ 0.3\ (m^3/m^3)$
4. Heat flux is increased as clay content or temperature of the cold store is increased.
5. The effect of increasing insulation thickness greater than 0.4 m or wall thickness greater than 0.3 m, on the heat flux is very small.
6. The heat flux is increased with the increase of cold store level and decreased as the width of the cold store is increased.
7. The heat flux is the main factor for the increase or the decrease of the time required to decrease the temperature below the cold store to zero ($0.0\ ^oC$).

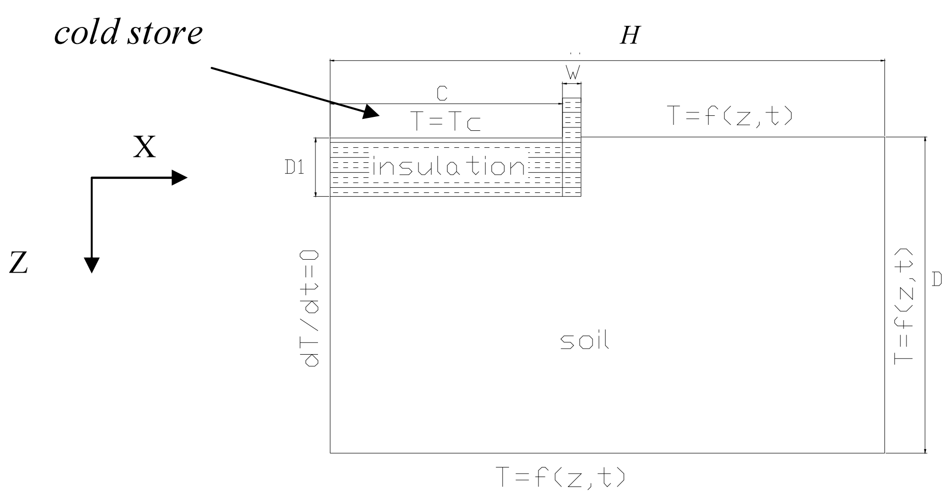


Fig.1. Schematic diagram of heat transfer model below cold store.

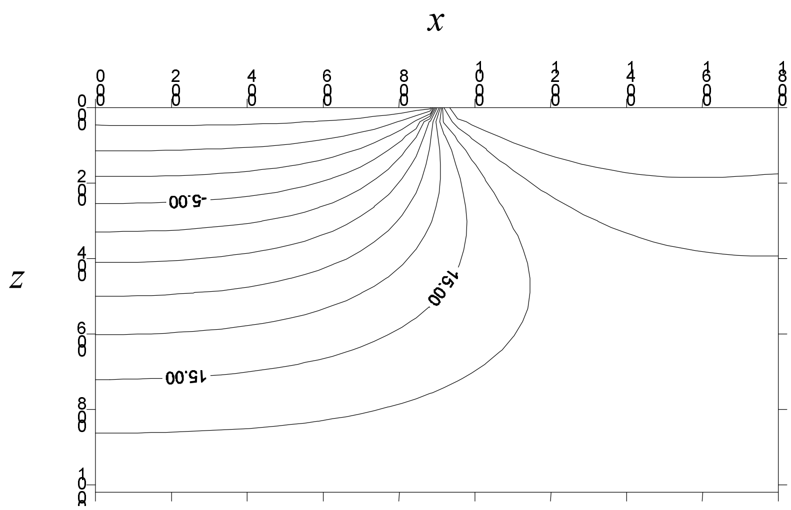


Fig.2. Isothermal line below cold store for the first case when the cold store floor is laid directly on the soil surface

(C = *9 m*, D1 = *0.4 m*, $T_c = -20^{\circ}C$,

volumetric water content = *0.3* m^3/m^3,

clay content = *30%*, $\rho = 1500\,kg/m^3$,

$k_s = 1.82\ W/m^{\circ}C$ and $\alpha = 0.079\,m^2/day$)

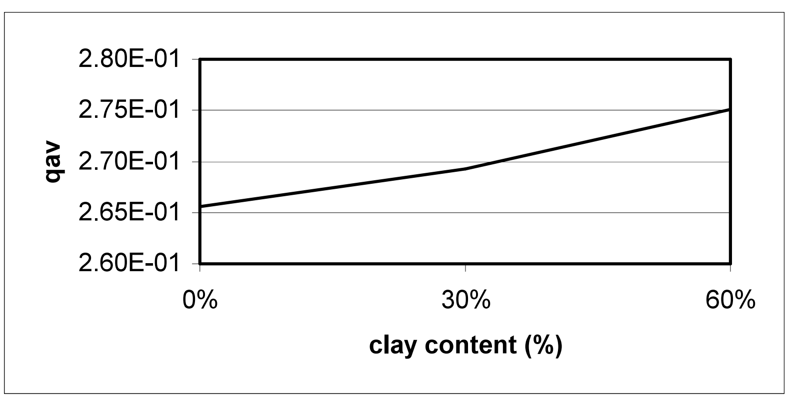


Fig.3. Variation of heat flux q_{av} $\left(W/m^2\right)$ with clay content (%).

(*C=9 m, D1=0.2 m,* $T_c = -20\ ^{\circ}C$, $\rho = 1800\ kg/m^3$,

volumetric water content=0.3 m^3/m^3, at *t=215 days*)

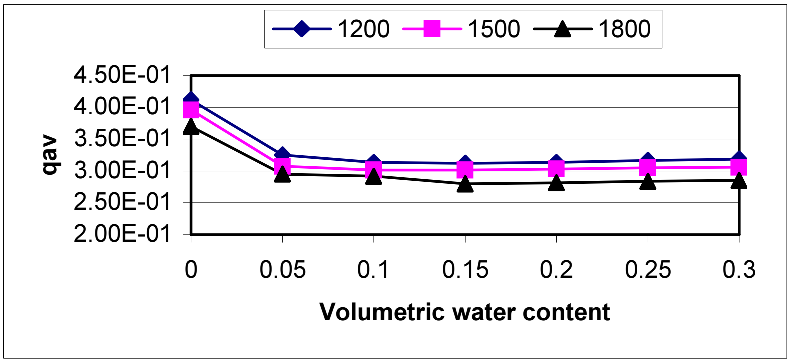


Fig.4. Variation of heat flux q_{av} $\left(W/m^2\right)$ with volumetric water content (m^3/m^3) for three different densities (ρ) (kg/m^3) (C=9 m, D1=0.2 m, $T_c = -20\ ^{o}C$, clay content=30 % at *t = 215 days*).

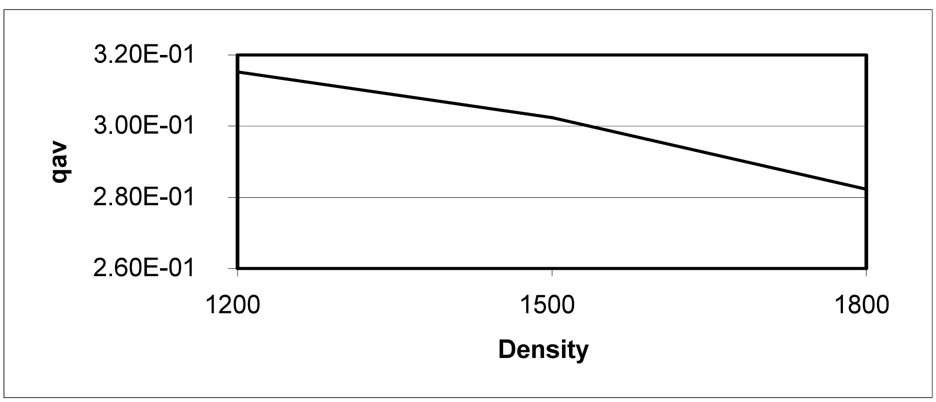


Fig.5. Variation of heat flux q_{av} $\left(W/m\ \right)$ with density (ρ) (kg/m^3) for (C=9 m, D1=0.2 m, $T_c = -20\ ^{o}C$, volumetric water content = 0.3 m^3/m^3 , clay content=30 % at *t = 215 days*).

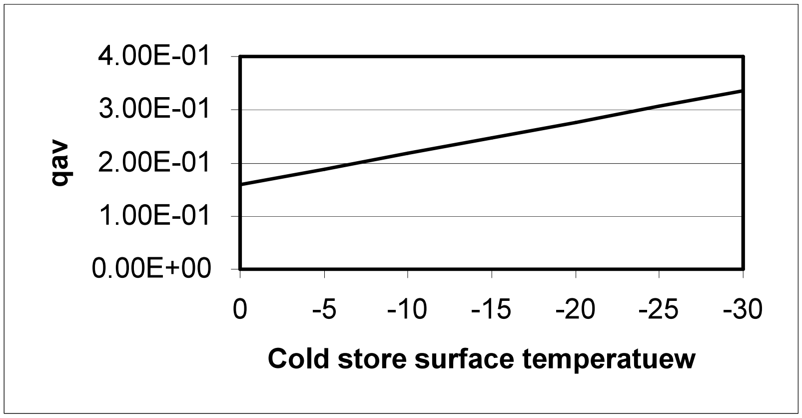


Fig.6. Variation of heat flux q_{av} $\left(W/m^2\right)$ with cold store surface temperature T_c (^{o}C) (C =9 *m*, D1= *m*, $\rho = 1800\ kg/m^3$, $T_c = -20\ ^{o}C$, volumetric water content = 0.3 m^3/m^3, clay content =30%, *t = 215 days*)

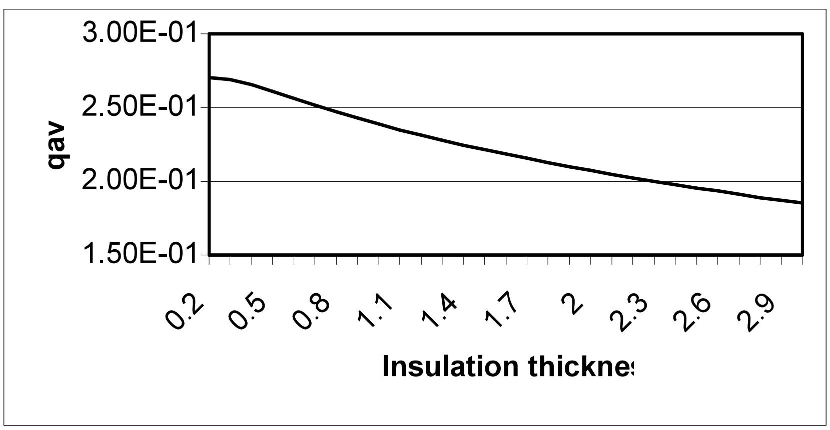


Fig.7. Variation of heat flux q_{av} $\left(W/m\ \right)$ with insulation thickness *D1* (*m*) polyurethane (C=9 m, $\rho = 1500\ kg/m^3$, $T_c = -20\ ^{o}C$, volumetric water content = 0.3 m^3/m^3, clay content = 30%, *t = 215 days*).

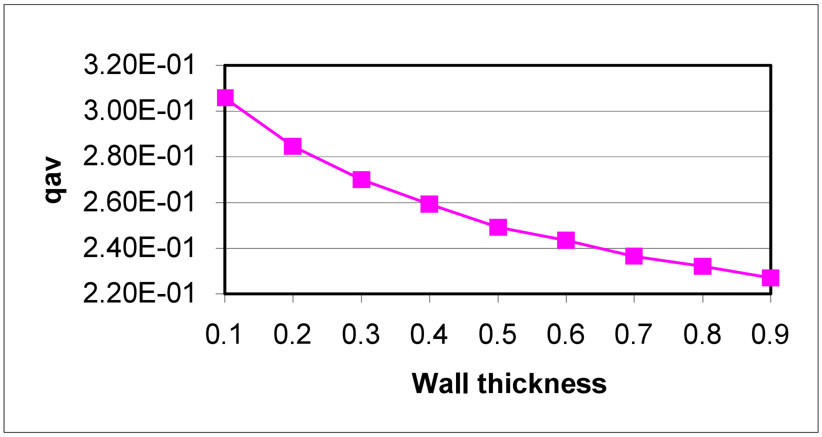


Fig.8. Variation of heat flux q_{av} (W/m^2) with wall thickness (*m*) (C=9 m, D1=0.2 m, $\rho = 1500\ kg/m^3$, $T_c = -20\ ^\circ C$, volumetric water content = 0.3 m^3/m^3, clay content = 30%, t = *215 days*).

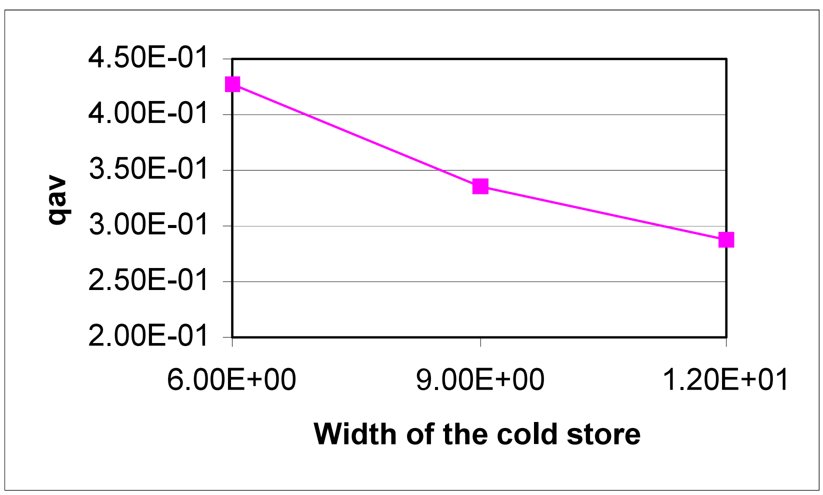


Fig.9. Variation of heat flux q_{av} $(W/m\ )$ with width of cold store (D1= 0.2 *m*, $\rho = 1500\ kg/m^3$, $T_c = -20\ ^\circ C$, volumetric water content = 0.3 m^3/m^3, clay content =30%, t = *215 days*).

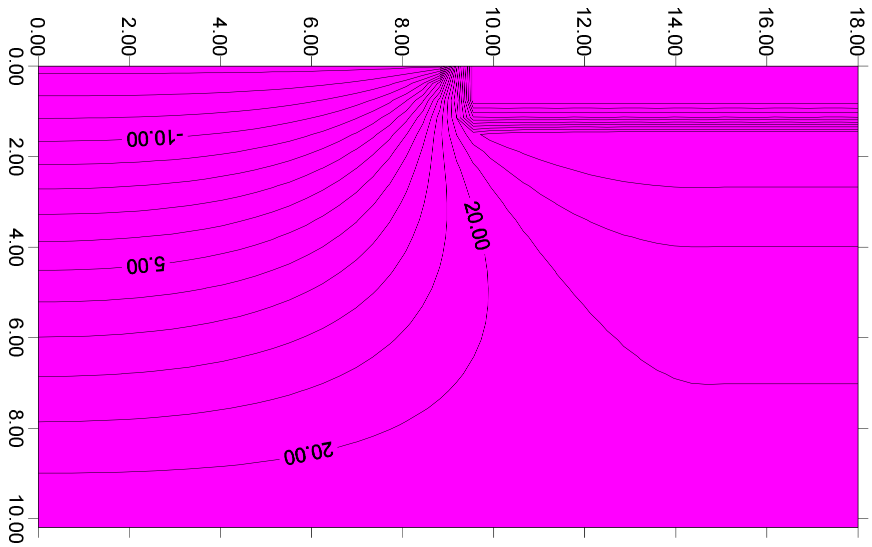


Fig.10. Isothermal line below cold store for the second case when the cold store floor is lifted up by *1.2 m* from the soil surface (C = *9 m*, D1 = *0.4 m*, $T_c = -20°C$, volumetric water content = *0.3* m^3/m^3, clay content = *30%*, $\rho = 1500\,kg/m^3$, $k_s = 1.82\ W/m°C$ and $\alpha = 0.079\,m^2/day$).

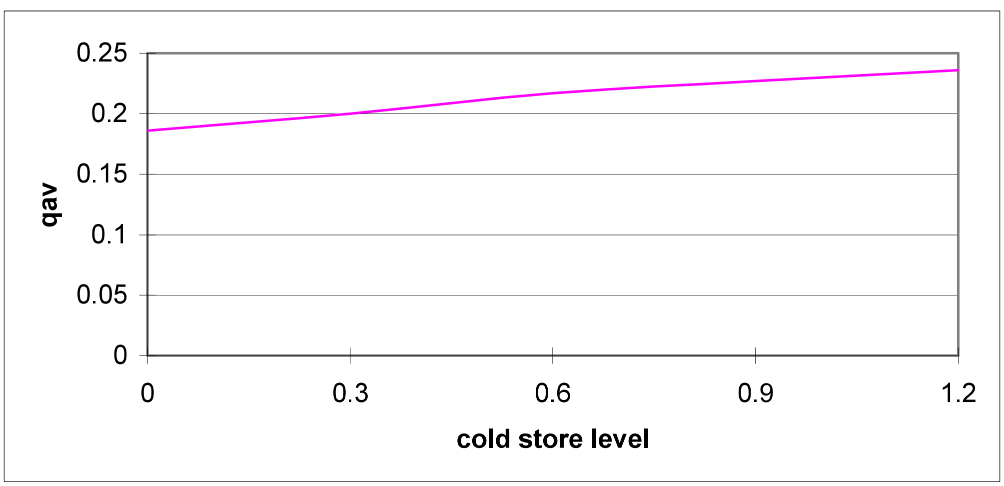


Fig.11. Variation of heat flux q_{av} (W/m^2) with different cold store level (C=9 m, D1=0.2 m, $\rho = 1500\ kg/m^3$, $T_c = -20\ °C$, volumetric water content = 0.3 m^3/m^3, clay content =30%, *t = 215 days*).

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